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Evaluation of forest snow processes models (SnowMIP2)

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[1] Thirty-three snowpack models of varying complexity and purpose were evaluated across a wide range of hydrometeorological and forest canopy conditions at five Northern Hemisphere locations, for up to two winter snow seasons. Modeled estimates of snow water equivalent (SWE) or depth were compared to observations at forest and open sites at each location. Precipitation phase and duration of above-freezing air temperatures are shown to be major influences on divergence and convergence of modeled estimates of the subcanopy snowpack. When models are considered collectively at all locations, comparisons with observations show that it is harder to model SWE at forested sites than open sites. There is no universal “best” model for all sites or locations, but comparison of the consistency of individual model performances relative to one another at different sites

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shows that there is less consistency at forest sites than open sites, and even less consistency between forest and open sites in the same year. A good performance by a model at a forest site is therefore unlikely to mean a good model performance by the same model at an open site (and vice versa). Calibration of models at forest sites provides lower errors than uncalibrated models at three out of four locations. However, benefits of calibration do not translate to subsequent years, and benefits gained by models calibrated for forest snow processes are not translated to open conditions.

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1. Introduction

[2] In the past, forest snow processes in land-surface models have been poorly replicated or even neglected [Essery, 1998; Pomeroy et al., 1998a], but recent development of more complex representations of forest canopies and snow processes as a result of experimental studies has led to the inclusion of more detailed considerations of forest snow processes in land-surface schemes [Niu and Yang, 2004; Wang et al., 2007; Yamazaki et al., 2007]. The purpose of this paper is to compare models that differ in their representation of forest snow processes, through comparison of model runs at paired forested and open sites, and to assess model performance in estimating snow water equivalent (SWE) or snow depth.

[3] Annual maximum snow extent covers ~ 47 million km^2 of the Northern Hemisphere each year [Robinson and Frei, 2000]. Although there are no direct estimates of the overlap between snow covered and forested areas, as boreal evergreen needleleaf forests (typical in subpolar boreal forest regions of the northern hemisphere) account for ~ 8.9 million km^2 [Secretariat of the Convention on Biological Diversity, 2001], a conservative estimate is that $\sim 19\%$ of Northern Hemisphere snow may overlap boreal forest. In nonpolar cold climate zones (Food and Agriculture Organization, Koeppen's climate classification map, 1977, <http://www.scribd.com/doc/2164459/KoppenGeiger-World-Climate-Classification-Map>), which again are typical of boreal forest regions, snow was estimated by Güntner et al. [2007] to account for 17% of terrestrial water storage. Consequently, it is important to obtain frequent, accurate estimates of forest SWE to: (1) evaluate Global Climate Models (GCM); (2) initialize hydrological forecast models; (3) estimate impacts on oceanic circulation of freshwater runoff from many large, poorly gauged catchments; and (4) to improve decision making in provision of drinking water, hydroelectric power, flood forecasting, agricultural irrigation and industrial uses in these environments. Uncertainty exists about the spatial distribution of boreal forests in the Northern Hemisphere under future climate scenarios. Although this uncertainty will be enhanced by fire and insect related disturbance [Kurz et al., 2008; McCullough et al., 1998], forest coverage is likely to spread north at the expense of tundra into seasonally snow covered areas [Denman et al., 2007]. Consequently, forest snow processes are likely to become more, rather than less, important in the future.

[4] The magnitude of snow accumulation and the timing and rate of ablation are very different between forested and nonforested sites. Hardy et al. [1997] reported that areas beneath tree canopies accumulated only 60% as much snow

as forest openings at the BERMS site in Canada, Koivusalo and Kokkonen [2002] found little difference between annual maximum SWE at clearing and forest sites in southern Finland, and Appolov et al. [1974] observed that ratios between annual maximum SWE at open and forest sites in Russia become greater in favor of forests when canopy density decreases and canopy type transitions from coniferous to broadleaf. Many complex and interacting processes account for these differences. Snow falling on a forest is partitioned into interception by the canopy and throughfall to the ground [Hedstrom and Pomeroy, 1998; Storck et al., 2002]. Intercepted snow may sublimate [Lundberg et al., 1998; Lundberg and Halldin, 1994; Lundberg and Koivusalo, 2003; Molotch et al., 2007; Montesi et al., 2004; Pomeroy et al., 1998b; Pomeroy and Schmidt, 1993; Schmidt, 1991], unload [MacKay and Bartlett, 2006] or melt within the canopy. Intercepted snow in dense forest canopies has been shown to have little influence on albedo [Pomeroy and Dion, 1996], but the influence of subcanopy snow rapidly increases the overall albedo of the landscape as canopy density decreases [Betts and Ball, 1997; Melloh et al., 2002; Nakai et al., 1999a; Ni and Woodcock, 2000]. Subcanopy snow is sheltered from wind, thereby decreasing turbulent transport, and receives less solar radiation owing to extinction and reflection [Hardy et al., 2004; Pomeroy and Dion, 1996; Tribbeck et al., 2006]. However, this may be offset to a degree by increased thermal radiation emitted from the canopy [Pomeroy et al., 2009; Sicart et al., 2004]. Together, these processes above and below the canopy influence energy and mass fluxes at the snow surface [e.g., Hardy et al., 1997, 1998; Link and Marks, 1999; Niu and Yang, 2004; Ohta et al., 1999; Suzuki and Nakai, 2008]. The structure of the forest canopy, and its representation within a model, greatly influence estimates of accumulation [Pomeroy et al., 2002] and rates of ablation [Otterman et al., 1988; Talbot et al., 2006]. By controlling the timing of snow cover depletion and the duration of melt, these influence the growing season and primary productivity of trees which depend on snowmelt infiltration water for thawing of frozen soils and for subsequent growth [Vaganov et al., 1999], in addition to the biological response to increases in air temperature where soils are unfrozen [Suni et al., 2003].

[5] Alternatives to numerical modeling to retrieve SWE in forests have not proven satisfactory. Globally, ground-based observations are sparse owing to problems of access in densely forested areas and lack of resources to maintain reliable observations. Remotely sensed observations are the only viable alternative to modeling SWE over such large areas, but forests are the most problematic land-cover classes for mapping snow covered area using optical sensors such as

MODIS [Hall et al., 1998; Hall and Riggs, 2007] and impose physical limitations on the interpretation of SWE from passive microwave sensors because of emissions from the forest overwhelming those from underlying snow [Chang et al., 1996; Foster et al., 1991; Parde et al., 2005].

[6] Representations of forest snow processes are simplistic in land-surface schemes owing to limitations imposed by our conceptual understanding of energy and mass exchanges, both within a forest canopy and between the canopy and the ground or atmosphere. The computational efficiency required by GCMs has imposed further limitations, but as the computational ability to represent complexity within environmental models is increasing rapidly [Jin et al., 1999a] these are becoming less important. Advances in conceptual understanding of the processes involved, interactions between processes and the dynamics of these processes over the cycle of a seasonal snowpack will be fundamental to future improvements in model representations of forest snow interactions.

[7] This paper describes SnowMIP2: an experiment to compare estimates of forest snowpack accumulation and ablation by a large group of models, ranging from simple degree day models (e.g., Snow-17), through land surface schemes of intermediate complexity (e.g., ISBA or CLASS), to complex snow-physics models (e.g., SNOWPACK or SNOWCAN) which include physically based representations of forest snow processes. Participating models covered a wide range of purpose or application. The main applications were hydrological, meteorological and climate research, although avalanche models and those used for forecasting purposes were also represented. Modeled estimates of SWE and snow depth were evaluated against in situ observations at five Northern Hemisphere locations, spanning a wide range of climates, hydrometeorological conditions and snowpack types. Comparison of modeled results at both forested sites and adjacent open sites at each of the five locations isolated the influence of the forest canopy on the whole population of modeled snowpack estimates. This influence was then examined in response to (1) meteorological events, (2) consistency of model performance, and (3) model calibration.

2. Experimental Design

2.1. Comparison to Previous Studies

[8] Many studies have compared energy or mass balance estimates from a small number (<10) of snow models [e.g., Essery et al., 1999; Fierz et al., 2003; Gustafsson et al., 2001; Jin et al., 1999b; Koivusalo and Heikinheimo, 1999; Pan et al., 2003; Pedersen and Winther, 2005; Yang et al., 1999b; Zierl and Bugmann, 2005]. However, only a few large model intercomparisons (>10 snow models) have been undertaken that explicitly consider snowpack outputs. An intercomparison of models of snowmelt runoff was first conducted by the World Meteorological Organization (WMO) [1986]. Following this study, AMIP1 [Frei and Robinson, 1998] and AMIP2 [Frei et al., 2005] evaluated continental-scale estimates of snow cover and mass in GCMs; PILPS 2(d) [Slater et al., 2001], PILPS 2(e) [Bowling et al., 2003] and Rhône-AGG [Boone et al., 2004] focused on evaluation of Land-Surface Scheme (LSS) simulations of snowpack and runoff in snow-dominated catchments, and SnowMIP [Etchevers et al., 2004] compared point simulations in nonforested conditions

from a broad range of models. Although much was learnt from the experimental design of these previous studies, strong efforts were made in SnowMIP2 to increase both the number of models and their diversity. The fact that 33 models (Table 1) participated in SnowMIP2 reflected a combination of: (1) enthusiasm and trust of the snow modeling community building on the success of previous studies, (2) flexibility in criteria required for model participation, for example, model purpose, adherence to Assistance for Land-surface Modeling Activities (ALMA) conventions [Henderson-Sellers et al., 1995, 1993; Polcher et al., 2000], and (3) timely interactions between the intercomparison organizers, data providers and participants to aid the data management process [Parsons et al., 2004]. As well as increased participation, it was important to increase the range of snow environments each model was evaluated against. As previous PILPS studies involved a single study catchment, albeit subdivided in PILPS2(e), and SnowMIP focused mainly on two alpine sites [Etchevers et al., 2004], the use of five different sites in the current study spanning a wide range of hydrometeorological and snowpack conditions was an important development.

2.2. Site Descriptions and Settings

[9] Models were evaluated at five Northern Hemisphere locations (Table 2). These locations span maritime, taiga and alpine seasonal snowpack types [Sturm et al., 1995], which result from different combinations of predominant climatic conditions, elevations and local topographies. In each location two sites were identified: a forested (canopy) site and an open (no canopy) site, which were at most 4 km from each other.

[10] Time series of shortwave and longwave radiation, total precipitation, air temperature, humidity and wind speed were obtained from automatic weather stations at each location, except for Hyytiälä, where longwave radiation was not measured. Precipitation measurements were corrected for undercatch and partitioned into snow, rain or mixed precipitation using algorithms supplied by the data providers (Table 3), based on their extensive local knowledge of the study sites and gauges.

[11] The hydrometeorological conditions at each location are summarized by the statistics in Table 4. Mean incoming shortwave radiation at each location varied inversely with latitude, from Fraser with the highest to Hyytiälä with the lowest. All sites had similar mean incoming longwave radiation other than Alptal, which was 20% greater than the next highest location, suggesting that Alptal was the cloudiest location on average. Alptal also had the highest snowfall of all five locations. The location with the next highest snowfall, Fraser, had only 57% of the total at Alptal while BERMS, with 22% of that of Alptal, had the lowest. BERMS was also the coldest location with a minimum recorded air temperature of -49°C and a mean temperature during the study period of -7°C , an effect of the continental climate. Alptal was the warmest location with a mean air temperature of 3°C , whereas the remaining three locations had mean air temperatures within 2°C of each other, averaging -2°C .

[12] All forested sites had evergreen needleleaf trees (fir, pine or spruce) of varying heights (7 to 27 m), providing year-round canopy coverage (Table 5). Meteorological data were collected above the canopy at each forest site. Canopy coverage was greater than 70% at all sites, which is ideal for testing models as current satellite microwave remote sensing

Table 1. Participating Models

| Snow Model | Model Identifier | References |
|---------------|------------------|---|
| 2LM | 2LM | <i>Yamazaki [2001], Yamazaki et al. [2004]</i> |
| ACASA | ACA | <i>Pyles et al. [2000]</i> |
| CLASS | CLA | <i>Bartlett et al. [2006], Verseghy [1991], Verseghy et al. [1993]</i> |
| CLM2-TOP | CLI | <i>Bonan et al. [2002], Niu and Yang [2003]</i> |
| CLM3 | CL3 | <i>Lewis et al. [2004], Oleson et al. [2004], Vertenstein et al. [2004]</i> |
| COLA-SSiB | COL | <i>Mocko et al. [1999], Sud and Mocko [1999], Sun and Xue [2001], Xue et al. [1991]</i> |
| CoupModel | COU | <i>Gustafsson et al. [2001] Karlberg et al. [2006]</i> |
| CRHM | CRH | <i>Hedstrom et al. [2001], Pomeroy et al. [2007]</i> |
| ESCIMO | ESC | <i>Strasser et al. [2008, 2002]</i> |
| ISBA-D95 | ISF | <i>Douville et al. [1995]</i> |
| ISBA-ES | ISE | <i>Boone and Etchevers [2001]</i> |
| JULES | JUL | <i>Blyth et al. [2006]</i> |
| MAPS | MAP | <i>Smirnova et al. [1997, 2000]</i> |
| MATSIRO | MAT | <i>Takata et al. [2003]</i> |
| MOSES | MOS | <i>Cox et al. [1999], Essery et al. [2003]</i> |
| NOAH-LSM | NOH | <i>Ek et al. [2003]</i> |
| RCA | RCA | <i>Kjellström et al. [2005], Samuelsson et al. [2006]</i> |
| S17 (SNOW-17) | S17 | <i>Anderson [1973, 1976]</i> |
| SAST | SAS | <i>Jin et al. [1999a, 1999b], Sun et al. [1999], Sun and Xue [2001]</i> |
| SiB 2.5 | SB2 | <i>Baker et al. [2003], Stöckli et al. [2007], Vidale and Stöckli [2005]</i> |
| SiB 3.0 | SB3 | <i>Baker et al. [2003], Sellers et al. [1996a, 1996b], Vidale and Stöckli [2005]</i> |
| SiBUC | SIB | <i>Tanaka and Ikebuchi [1994]</i> |
| SNOWCAN | SNO | <i>Tribbeck [2002], Tribbeck et al. [2006, 2004]</i> |
| SNOWPACK | SNP | <i>Bartelt and Lehning [2002], Lehning et al. [2002a, 2002b]</i> |
| SPONSOR | SPO | <i>Shmakin [1998]</i> |
| SRGM | SRG | <i>Gelfan et al. [2004]</i> |
| SSiB3 | SSI | <i>Xue et al. [1991, 2003]</i> |
| SWAP | SWA | <i>Gusev and Nasonova [1998, 2000, 2002, 2003]</i> |
| TESSEL | TES | <i>van den Hurk et al. [2000], Viterbo and Beljaars [1995]</i> |
| UEB | UEB | <i>Tarboton and Luce [1996]</i> |
| UEBMOD | UEM | <i>Hellström [2000]</i> |
| VEG3D | VEG | <i>Braun and Schädler [2005]</i> |
| VIC | VIC | <i>Cherkauer et al. [2003]</i> |

techniques can only reliably retrieve snowpack properties at canopy densities less than 60–70% [Cline et al., 2004; Pulliainen et al., 2001]. Open sites consisted of either cut grass or previously cleared forest. Deforestation occurred at the open site in 1985 at Fraser and in 2000 at BERMS. The BERMS site was subsequently scarified in 2002 and no significant regrowth has taken place, while on the Fraser open site some small trees (2–4 m) have regrown. However, regrowth is very sparse at the Fraser open site and meteorological and snowpack measurements were made in gaps between any regrowth.

2.3. Experimental Procedures

[13] At each site, models were provided with meteorological, canopy and soil data. Modeling groups were strongly encouraged to use these data as given. However, of the 33 models, 4 could not use snowfall as prescribed and applied their own methods for partitioning total precipitation. Repartitioning led almost invariably to a reduction in snowfall; maximum decreases across all locations were 3% (NOH), 13% (SNO) and 29% (COL and CRH). As in PILPS2(e), modelers were encouraged to use in-house methods to determine model parameters. SWE data were provided for the first year at the forest sites only to allow calibration of model parameters, except for Hitsujigaoka where simulations were only performed for 1 year. Fifty-eight percent of models took this option to calibrate. All other SWE and depth data were withheld to allow independent evaluation. The models that calibrated mostly adjusted canopy parameters that were not relevant to open simulations. However, exceptions were adjustments of fresh snow albedo (NOH and SSI), snow den-

sity (VEG), snow roughness length (VIC), stability adjustment (SSI), soil thermal properties (UEM) and snow cover fraction parameters (S17).

[14] Fifty-seven components of the energy and mass balance, including state variables, fluxes and snow profile information were requested at 30-min time intervals from participating models. State variables were required at the end of each time step, fluxes were averaged over a time step and changes in energy and mass were accumulated. Models that represented fractional snow cover returned outputs as grid box averages. Before returning modeled results each modeling group was encouraged to perform consistency checks for conservation of energy and mass fluxes. Energy fluxes were required to balance, when averaged over the length of each simulation, within 3 W m^{-2} and mass fluxes within 3 mm a^{-1} [Bowling et al., 2003]. Although output data were based on ALMA conventions, additions were made to account for canopy snow processes and ASCII formatting of outputs as well as Network Common Data Form (NetCDF) was permitted. Model performance was then evaluated using SWE or snow depth (where available) at each site.

[15] Information describing the substrate at each site was required by many models, primarily for initialization of model runs in autumn before snow cover formation. Profiles of soil temperature and moisture at between three and six levels within the top 150 cm for each site (except Alptal, where a single measurement at a depth of 20 cm in the forest soil was available) were given for the start dates of each of the simulation periods listed in Table 4. Averages are presented in Table 6 and exhibit a range between both sites and locations.

Table 2. Physical Characteristics of Study Locations

| Location | Site | Latitude | Longitude | Distance From Forest (m) | Elevation (m) | Slope Aspect/Angle | Soil Composition | Snowpack Type [after Sturm et al., 1995] | Site Reference(s) |
|----------------------|-------------|----------|-----------|--------------------------|---------------|--------------------|---|--|--|
| Alptal (Switzerland) | Forest | 47°03 N | 8°48 E | - | 1185 | West/3° | 44% clay, 44% silt | Alpine | <i>Stahli and Gustafsson</i> [2006] |
| BERMS (Canada) | Open Forest | - | - | 200 | 1220 | West/11° | Same as Forest | Same as Forest | Same as Forest |
| | Forest | 53° 55 N | 104° 42 W | - | 579 | Level | Sandy loam in top meter, clay loam beneath; 10–20% coarse material | Taiga | A. Barr et al., BERMIS climate data, southern study area, 2000 (http://bermis.ccrp.ec.gc.ca/data/data_doc/BERMS_main.doc) |
| Fraser (USA) | Open Forest | - | - | 4000 | 579 | Level | Same as Forest | Same as Forest | Same as Forest |
| | Forest | 39°53 N | 105°53 W | - | 2820 | Northwest/17° | Sandy glacial till | Alpine | <i>Elder and Goodbody</i> [2004] |
| Hitsujigaoka (Japan) | Open Forest | - | - | 45 | 2820 | Northwest/17° | Same as Forest | Same as Forest | Same as Forest |
| | Forest | 42°59 N | 141°23 E | - | 182 | Level | Sandy soil (94% sand, 3% clay), organic layer 0–10 cm deep in forest only | Maritime | <i>Nakai, et al.</i> [1999a, 1999b], <i>Sameshima et al.</i> [2009], <i>Suzuki and Nakai</i> [2008] |
| Hyytiälä (Finland) | Open Forest | - | - | 2500 | 182 | Northeast/2.5° | Same as Forest | Same as Forest | Same as Forest |
| | Forest | 61°51 N | 24°17 E | - | 181 | Level | Loam (clay loam 0–20 cm and light clay in open area) | Taiga | <i>Finnish Meteorological Institute</i> [2008], <i>Makonen et al.</i> [2006], <i>Sevanto et al.</i> [2006] |
| | Open | - | - | 500 | 154 | Level | Same as Forest | Same as Forest | Same as Forest |

Table 3. Precipitation Partitioning (Between Rain and Snow) Algorithms and Wind Undercatch Corrections Applied to Raw Precipitation Data at Each Location^a

| Location | Snow Fraction (F_{snow}) as a Proportion of Total Precipitation | Wind-Corrected Precipitation Rate (P_{cor}) |
|----------------------|--|---|
| Alptal (Switzerland) | $F_{snow} = \begin{cases} 0 & T_a \geq 1.5^\circ C \\ \frac{1-T_a}{1.5} & 0^\circ C < T_a < 1.5^\circ C \\ 1 & T_a \leq 0^\circ C \end{cases}$ | No (sheltered site) |
| BERMS (Canada) | $F_{snow} = \begin{cases} 0 & T_a \geq 6^\circ C \\ 1 + 0.04666T_a - 0.15038T_a^2 - 0.01509T_a^3 + 0.0204T_a^4 - 0.00366T_a^5 + 0.0002T_a^6 & 0^\circ C < T_a < 6^\circ C \\ 1 & T_a \leq 0^\circ C \end{cases}$ | $P_{cor} = \begin{cases} \frac{P_{obs}}{P_{obs} - 0.135U} & T_a < 2^\circ C \\ P_{obs} & T_a \geq 2^\circ C \end{cases}$ |
| Fraser (USA) | $F_{snow} = \begin{cases} 0 & T_a \geq 2^\circ C \\ 1 & T_a < 2^\circ C \end{cases}$ | No (sheltered site) |
| Hitsujigaoka (Japan) | $F_{snow} = \begin{cases} 1 - 0.5 \exp \left[-2.2(1.1 - T_w)^{1.3} \right] & T_w < 1.1^\circ C \\ 0.5 \exp \left[-2.2(T_w - 1.1)^{1.3} \right] & T_w \geq 1.1^\circ C \end{cases}$ | $P_{cor} = \begin{cases} P_{obs}(1 + m_{rain}U) & m_{rain} = 0.128 \\ P_{obs}(1 + m_{snow}U) & m_{snow} = 0.0192 \end{cases}$ |
| Hyytiälä (Finland) | $F_{snow} = \begin{cases} 0 & T_a \geq 2^\circ C \\ 1 - \left(\frac{T_a}{2} \right) & 0^\circ C < T_a < 2^\circ C \\ 1 & T_a \leq 0^\circ C \end{cases}$ | No (sheltered site) |

^a T_a , air temperature; T_w , wet bulb temperature; P_{obs} , observed precipitation rate.

Table 4. Meteorological Characteristics of Study Locations^a

| Observation periods(s) | Location | Site | SW Incoming (Wm ⁻²) | | LW Incoming (Wm ⁻²) | | Snow (mm) | | Rain (mm) | Air Temperature (°C) | | Wind Speed (m s ⁻¹) | | Relative Humidity (%) | | |
|---------------------------|-----------------------|--------|------------------------------------|---------|------------------------------------|------------------|------------------|------------------|------------------|----------------------------|---------|------------------------------------|------------|-----------------------------|------|---------|
| | | | Mean | Maximum | Mean | Maximum | Total | Minimum | Total | Mean | Minimum | Measurement | Height (m) | | Mean | Maximum |
| | | | | | | | | | | | | | | | | |
| 1/10/02 to 31/5/03 | Alptal | Forest | na | na | na | na | na | na | na | 4 | -15 | 35 | 1 | 11 | 78 | |
| 1/10/03 to 23/5/04 | (Switzerland) | Open | 99 | 948 | 302 | 421 | 1218 | 184 | 1590 | 2 | -18 | 3.5 | 2 | 12 | 78 | |
| 1/9/02 to 30/4/03 | BERMS | Forest | 87 | 929 | 241 | 406 | 271 | 104 | 148 | -6 | -39 | 28 | 3 | 11 | 75 | |
| 1/9/03 to 30/4/04 | (Canada) | Open | 89 | 905 | 244 | 411 | 109 | 272 ^b | 146 ^b | -7 | -49 | 5 | 2 | 11 | 76 | |
| 1/11/03 to 31/5/04 | Fraser | Forest | 145 | 1132 | 236 | 352 | na | 118 | na | -2 | -25 | 30 | 2 | 10 | 64 | |
| 1/10/04 to 31/5/05 | (USA) | Open | 138 | 1119 | 248 | 377 | 128 | 700 | 46 | -3 | -27 | 4 | 1 | 4 | 67 | |
| 1/12/97 to 30/4/98 | Hitsujiagaoka | Forest | 119 | 947 | 252 | 389 | 156 | na | na | -1 | -17 | 9.2 | 2 | 7 | 73 | |
| 1/10/03 to 29/4/04 | (Japan) ^c | Open | na | na | na | na | 188 | 34 | 34 | -1 | -20 | 10 | 2 | 11 | 76 | |
| | Hyytiälä ^d | Forest | 49 | 691 | 255 ^e | 345 ^e | 326 ^f | 180 ^e | 290 ^f | -2 | -21 | 17 | 2 | 8 | 83 | |
| 1/10/04 to 29/4/05 | (Finland) | | | | | | | | | | | | | | | |

^aFor observation periods, read, for example, 1/10/02 as 1 October 2002; na denotes data not available. Model driving data obtained from other site at each respective location.

^bPrecipitation was observed in a clearing adjacent to the forested site. Total snowfall and rainfall at the open site used precipitation observed adjacent to the forest site that was repartitioned using air temperature and wind speed observed at the open site.

^cOne year of observations only.

^dAt Hyytiälä, forest meteorology data were used for simulations at the open site.

^eData modeled from air temperature and relative humidity following *Liston and Elder* [2006].

^fPrecipitation observed at the open site 1 km from forest site.

Table 5. Canopy Characteristics and Methods of Canopy Description at Study Locations^a

| Location | Forest Type | Percent Coverage | Snow-Free Albedo | | Forest Height (m) | Open Vegetation Type | Methods and Reference(s) | | | | | |
|-----------------------|------------------------------|------------------|------------------|-------------------|-------------------|--|--------------------------|-----|------|-----|------|---|
| | | | Forest | Open | | | Le | Lt | L | Ω | α | |
| Alptal (Switzerland) | Norway spruce and silver fir | 96 | 0.11 | 0.19 | 25 [35] | Short grass [3.5] | 2.5 | 4.2 | na | na | na | Hemispherical photos analysis using Hemisfer software (P. Schleppi, http://www.wsl.ch/dienstleistungen/hemisfer/index_EN?redir=1& , accessed 21 Jan 2007) |
| BERMS (Canada) | Jack pine | 72 | 0.11 | 0.16 | 12 – 15 [28] | Herbaceous colonizers and severely disturbed bare soil [2–5] | 1.66 | 2.7 | 1.84 | na | 0.32 | TRAC [Chen and Cihlar, 1995; Chen et al., 1997] |
| Fraser (USA) | pine, spruce, and fir | na | 0.05 | 0.1 | 27 [30] | Very sparse 2- to 4-m-tall trees [4] | 3 | na | 3.68 | 0.6 | 0.25 | Destructive sampling and allometric (diameter at breast height) relationships [Kauffman et al., 1982] |
| Hitsujiagaoka (Japan) | Todo fir | 90 | 0.12 | 0.17 ^b | 7 [9.2] | Short grass [1.5–10] | 3 | 6 | na | na | na | Destructive sampling [Nakai et al., 1999a; T. Yamazaki, personal communication, 2007] |
| Hyytiälä (Finland) | Scots pine | 70 | 0.15 | na | 15 [17] | Short grass [1.5] | 2.4 | 3 | na | 0.6 | 0.25 | All-sided leaf index from inventory methods and local conversion factors [Jésala et al., 2005] |

^aSee text for definition of symbols; na denotes data not available.

^bAssumed.

Table 6. Soil Characteristics of Study Locations^a

| Location | Maximum Profile Depth (cm) | Average Temperature (°C) | | Average Moisture (m ³ m ⁻³) | |
|----------------------|----------------------------|--------------------------|----------------|--|-------------------------|
| | | Forest | Open | Forest | Open |
| Alptal (Switzerland) | 45 | 5 ^b | 5 ^b | Saturation ^b | Saturation ^b |
| BERMS (Canada) | 150 | 14 | 19 | 0.05 | 0.11 |
| Fraser (USA) | 50 | 4 | 3 | 0.09 | 0.08 |
| Hitsujigaoka (Japan) | 150 | 6 | 7 | 0.43 | na |
| Hyytiälä (Finland) | 50 | 8 | na | 0.28 | na |

^aNotation: na denotes data not available.^bEstimated.

2.4. Data Uncertainties

[16] For detailed descriptions of the instrumentation setup at each site see the site references in Table 2. As data were obtained at five separate locations, there is inevitable spread in the instrumentation type, continuity and quality of data used for model input and evaluation. It is beyond the scope of this paper to provide a full breakdown by site of uncertainties associated with each variable. Consequently, it is essential to stress that the main purpose of this study is to assess relative rather than absolute model performance. With this in mind, it is important to highlight two major sources of data uncertainty within intercomparisons of this type: precipitation and SWE evaluation data.

[17] Reliable measurement of precipitation in cold environments is a difficult task [Yang *et al.*, 1999a] and has been problematic for previous intercomparisons, for example causing overestimation in PILPS2(d) and requiring reruns to correct for undercatch in PILPS2(e). Uncertainties are primarily caused by differences in gauging methods, the use of wind corrections to rectify undercatch, evaporation and partitioning of total precipitation into snow and rain, all of which may compound on each other throughout the duration of a seasonal snowpack. Methods employed to account for each of these factors tend to be highly site specific.

[18] There is no universally accepted method or set of instruments for measuring snow depth, density and water equivalent, and the application of a particular method may even vary widely with user and site conditions [Pomeroy and Gray, 1995]. In general, snow depth is highly variable over space and snow density is less variable, but covariance between depth and density can bias estimates of mean SWE obtained by multiplying means of depth and density calculated from samples of different sizes [Shook and Gray, 1994]. Spatial autocorrelation of SWE requires that transects should be long enough to obtain reliable statistics and yet short enough to remain within a single landscape unit. Exact errors for SWE measurement techniques are difficult to quantify, but mean errors of up to 10.5% for a range of snow samplers have been observed [Goodison *et al.*, 1981]. At the sites used here, gravimetric measurements of snow density used either small scoop samplers in snowpits or bulk snow tube samplers at points on transects. SWE measurements were made in terrain representative of the site, preferably at the site of the meteorological tower but not necessarily (e.g., observations were made away from the tower at the BERMS site to prevent influencing flux measurements). Standard errors in mean SWE observations ranged from 1 to 52 mm between locations and were consistently greater at open than forest sites at each location.

2.5. Representation of Canopies

[19] Different in situ methods were used at each location to measure forest canopy structure (Table 5). Also, many different methods exist to relate those in situ measurements to parameters or empirical relationships in models that describe the forest canopy. This variation in measurement and model representation is a fundamental source of uncertainty in forest snow process modeling that is currently unquantifiable. Without knowledge of relative uncertainties between different methods of representing canopy structure the best that can be done is to carefully define the relations between measurement methods and a common parameter, leaf area index (LAI), following the definitions and notations of Chen *et al.* [1997].

[20] Optical measurements of LAI are based on inversions of Beer's Law, variants of which are commonly used to parameterize subcanopy radiation. Viewing a canopy from the ground, the gap fraction at zenith angle θ is

$$P(\theta) = \exp \left[-\frac{G(\theta)}{\cos \theta} \Omega L_t \right],$$

where L_t is a plant area index including leaves and wood, and G is a projection coefficient determined by leaf orientations; for example, G is equal to $\cos \theta$ for horizontal leaves or 0.5 for randomly oriented leaves. Beer's Law can be obtained by assuming a random spatial distribution of canopy elements and then introducing the factor Ω to account for clumping. The product $L_e = \Omega L_t$ is an effective plant area index; L_e and Ω can both be determined by measurements of gap fraction or transmission at multiple zenith angles. Chen *et al.* [1997] defined LAI, L , as "one half the total green leaf area per unit ground surface area" and calculated it as

$$L = (1 - \alpha) \frac{L_e}{\Omega},$$

where α is the ratio of woody to total area, which is difficult to measure optically for evergreen canopies. As both needles and stems intercept radiation and precipitation, the plant area indices L_t and L_e in Table 5 were the main parameters presented to modelers.

[21] All of the open sites, apart from Fraser, have short vegetation that is seasonally submerged by snow. Exact values of vegetation parameters for these sites were expected to have little influence on snow simulations, so it was suggested that vegetation height and LAI should be set to small nominal values (e.g., 5–10 cm height, LAI = 1.0).

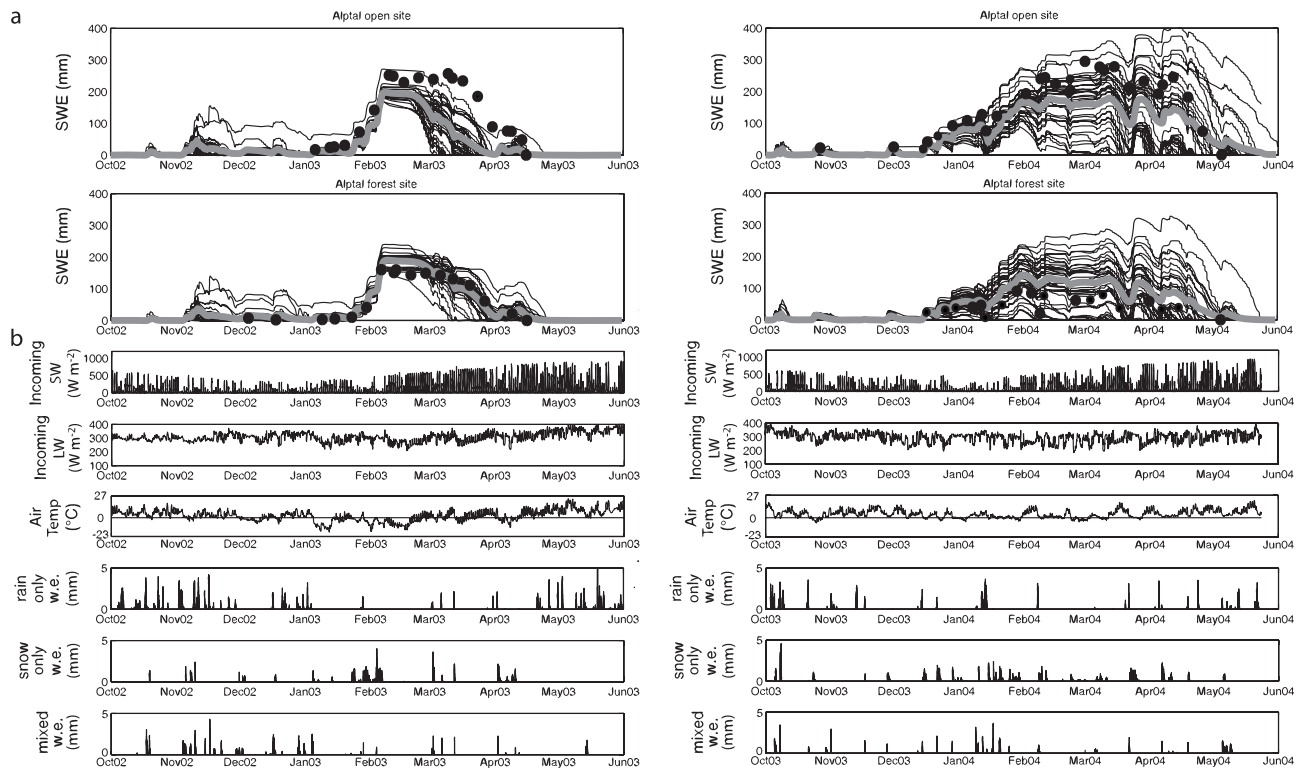


Figure 1. (a) Alptal observed SWE (black dots), individual modeled estimates (black lines), and the average of all modeled estimates (gray line). (b) Meteorological variables; see text for definition of mixed precipitation.

2.6. Data Reconstruction and Manipulation

[22] The use of synthetic data to fill gaps in model input data is common in intercomparisons [Bowling *et al.*, 2003], but very little reconstruction (<1%) was necessary in this study. Short gaps of one time step were filled by linear interpolation. If gaps were greater than a 30-min time step and the same variable was recorded at either a different height on the same tower or in close proximity on a different tower, then a fitting relationship was derived during periods of consecutive data. The relationship was then used to fill missing data gaps. Where other data were unavailable to construct fitting relationships, missing data segments were filled using procedures following Liston and Elder [2006]. The only entirely missing time series, incoming longwave radiation at Hyytiälä, was reconstructed in this manner.

[23] To maintain consistency between input data used by different models, radiation and precipitation rates at sloping sites (Alptal and Fraser) were projected to unit area parallel to the slope. Energy and mass balance simulations could, therefore, be carried out as if these sites were level. Constant surface pressures were prescribed as a function of the site elevation.

3. Results and Discussion

[24] Model results and observations for the five sites are shown in Figures 1–5. Analyses of results are split into three sections: (1) range of model performance (both at individual sites and summarized over all sites), (2) consistency of model performance, (3) influence of calibration and use of precipitation data on model performance.

3.1. Range of Model Performance

[25] Variations in meteorological inputs and canopy types across the five locations provide a wide range of causes for modeled estimates of SWE or snow depth to both diverge and converge throughout a winter. Such divergence can broadly be considered a consequence of: (1) how a model partitions precipitation via canopy interception and unloading processes for snow, rain or mixed precipitation, or (2) how a model calculates the rates of melt and sublimation and how it drains liquid from the canopy and subcanopy snowpacks.

[26] Differences in partitioning of precipitation falling as snow between the canopy and the ground commonly caused model divergence during snowpack accumulation, for example, the result of three successive heavy snow events in late January/early February 2003 at Alptal (Figure 1). Although this was evident at all locations, it is particularly important up to the point of maximum seasonal accumulation at BERMS (Figure 2) and Fraser where winter rainfall is rare (Figure 3). This is due to intensely cold continental midwinter temperatures at BERMS and a binary precipitation phase threshold of $2^{\circ}C$ at Fraser, although winter temperatures are less extreme. Snowfalls at both of these locations tend to be frequent but small in magnitude so divergence of modeled estimates is incremental but important when compounded.

[27] Mixed precipitation and rain-only events had a greater influence on the spread of modeled estimates at Alptal, Hitsujigaoka (Figure 4), Hyytiälä (Figure 5), and, at the start of 2002–2003 only, at BERMS. As well as partitioning mass between the canopy and the ground, models differed over whether to discharge meltwater or absorb and refreeze it. Increased divergence between modeled estimates due to rain

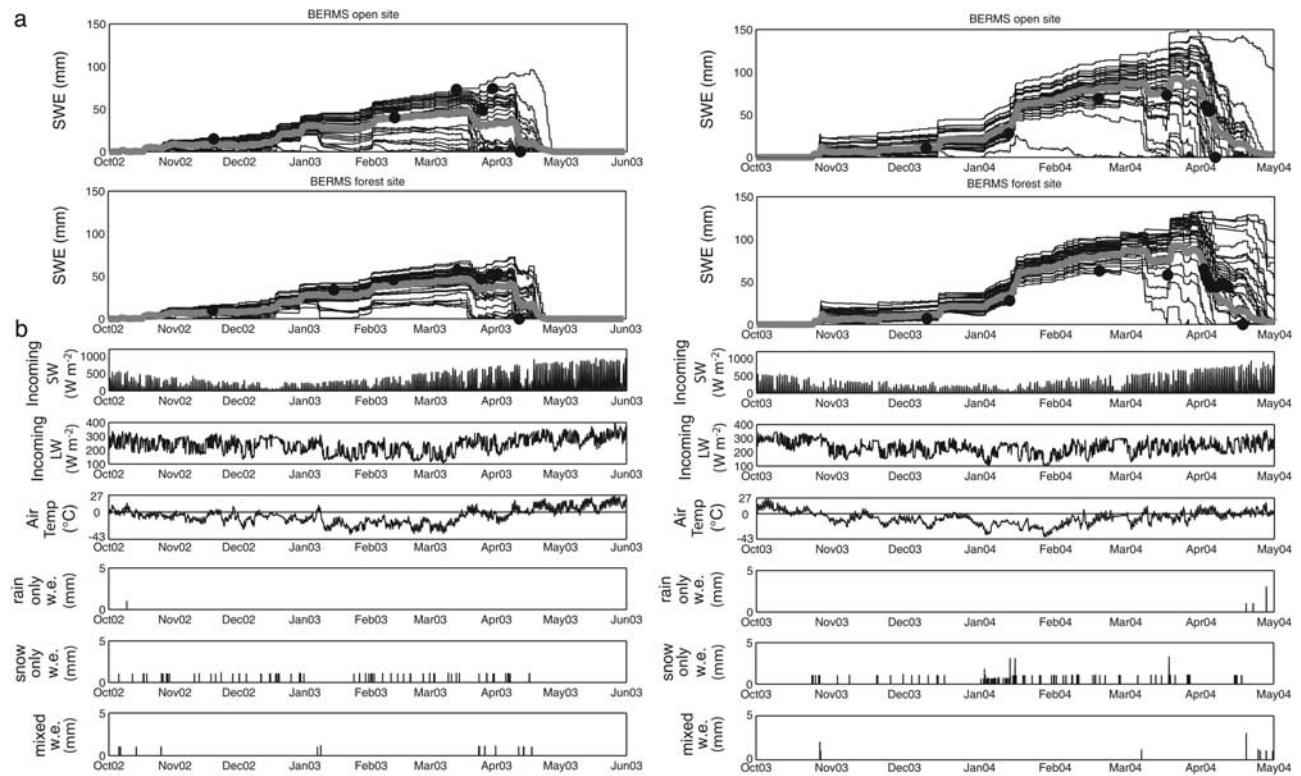


Figure 2. As in Figure 1 but for BERMS.

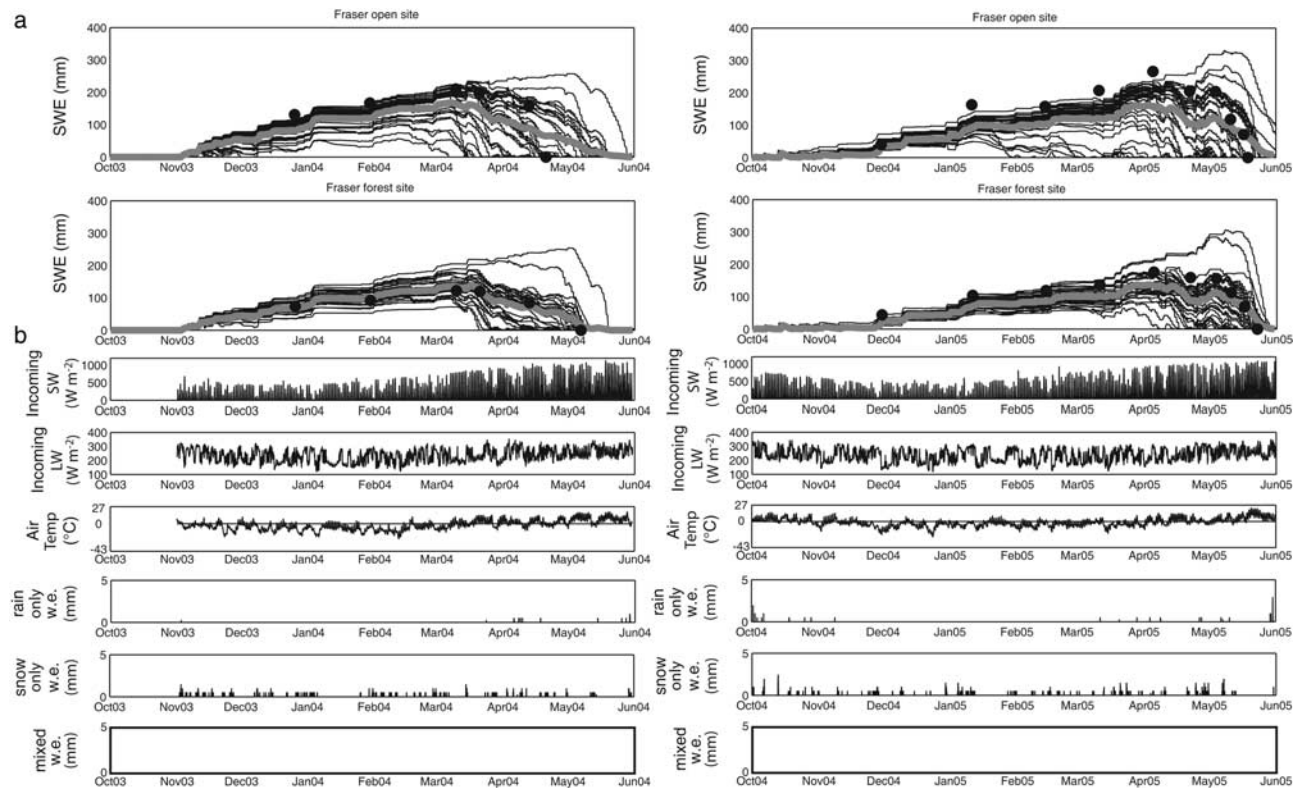


Figure 3. As in Figure 1 but for Fraser.

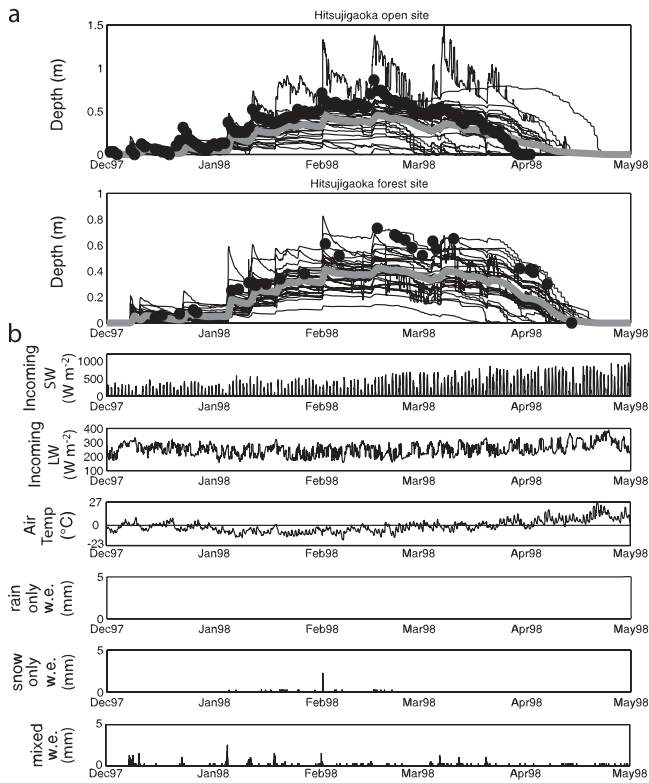


Figure 4. As in Figure 1 but for Hitsujigaoka, and for snow depth rather than SWE in Figure 4a.

on snow, in conjunction with air temperatures above 0°C, was particularly evident at Hyttiälä in late December 2003 and early January 2005. Frequent mixed precipitation events at Hitsujigaoka, which were common below air temperatures of 0°C owing to the partitioning algorithm employing wet bulb temperatures (Table 3), were the dominant influence on model divergence throughout the winter. Conversely, close to the start of snow accumulation in late October 2003 at BERMS, a single mixed precipitation event followed by modeled melt during subsequent days was the single biggest influence on model divergence throughout the following 4 months.

[28] Mixed precipitation and rain on snow also caused convergence of modeled estimates. Energy, either advected directly by rain or through latent heat release on refreeze, altered the thermal state of the snow to cause greater melting and runoff. This was demonstrated in mid-January 2004 at Alptal when convergence of modeled estimates resulted from a mixed precipitation event followed shortly by a heavy rain-only event.

[29] Increased sensible and radiative heat fluxes into the snowpack commonly caused melt and subsequent runoff, which resulted in model divergence during snowpack accumulation. At all locations, model divergence through melt events during accumulation were dominated by air temperatures rising above 0°C rather than increases in incoming short-wave radiation.

[30] Three types of raised air temperature events were evident across the five locations during snowpack accumulation. The first type of event was when air temperatures briefly exceeded 0°C and then dropped below 0°C for consecutive days. Not all models were sensitive to these

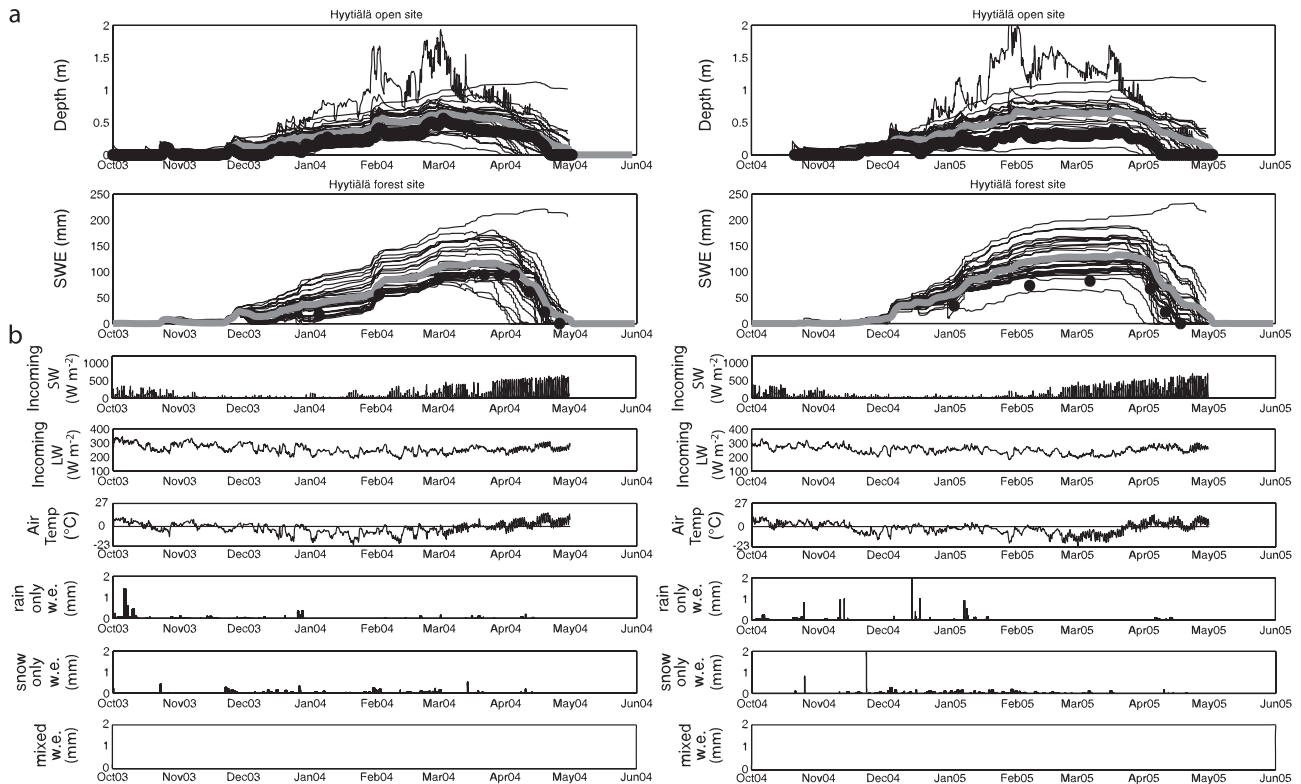


Figure 5. As in Figure 1, but for Hyttiälä, and for SWE (forest site) and snow depth (open site) in Figure 5a.

events, but for example, at BERMS in early March in 2004, air temperatures exceeded 0°C for less than a 2-day period, resulting in large mass losses from four models and the maximum range for that site. Second, consecutive days where air temperatures exceeded 0°C during the day but dropped below freezing at night were common, particularly at Fraser (January 2004 and both January and February 2005), and Hitsujigaoka (late February and early March 1998). However, such diurnal cycles around 0°C did not cause noticeable melt at Fraser, and may have had a slight impact on reduction of depth at Hitsujigaoka in combination with compaction. Finally, events when air temperature exceeded 0°C for more than two consecutive days caused considerable melt-induced model divergence. Of all the possible meteorological influences on modeled SWE, this type of event had the largest impact on increasing divergence of SWE at all locations. The impact of a single event of this type was evident at Hyytiälä. After over two months of subzero air temperatures, in late March 2005 consecutive days above 0°C caused some models to reduce forest SWE before the model with the largest SWE estimates reached the point of maximum seasonal accumulation, thus causing an increase in model divergence. Multiple events of this type occur throughout the accumulation period at Alptal; three events in February to mid-March 2004 caused increasing melt-induced divergence between models as progressively greater numbers of models approached melt-out before the time of maximum modeled SWE.

[31] To compare model performance between differently sized snowpacks, Table 7 shows root mean squared errors (RMSE) in modeled SWE normalized by standard deviations of the observations (errors in snow depth, rather than SWE, are given for Hitsujigaoka and the Hyytiälä open site). Minimum and maximum RMSE provided an indication of good or poor model performance at each site and mean RMSE provided a performance indicator of all models considered together.

[32] At sites where SWE observations were recorded and in years for which calibration data were not supplied (the single year at Hitsujigaoka and the second year at other locations), minimum normalized RMSE at forest sites ranged from 0.2 to 0.8 and maximum normalized RMSE ranged from 2.1 to 6.9. At Hitsujigaoka, where only depths were recorded, the range of model performance at the forest site was smaller (0.3 to 1.7). Model performance was better at open than forest sites. At open sites, minimum normalized RMSE ranged from 0.2 to 0.5 and maximum normalized RMSE ranged from 1.7 to 2.7, or 0.3 for minima and 1.7 to 5.6 for maxima where only snow depths were available.

[33] Figure 6 summarizes individual model performances using normalized RMSE at open and forest sites. It clearly shows that there is not one best model, nor a subset of ‘better’ models, although the spread in normalized RMSE of individual models is generally greater at forest sites than open sites. Owing to differences in uncertainties associated with meteorological and snowpack measurements, there was not sufficient difference between model performances to confidently claim that a particular model had consistently better performance than another. Consequently, of greater interest is whether or not there was much consistency in individual model performance, how useful calibration was and whether or not a model used precipitation in the prescribed manner.

Table 7. Mean, Range, and Total Normalized RMSE Between Modeled Estimates and Observations by Location, Site, and Year^a

| Location | Years | Forest | | | | | | Open | | | | | | | |
|-------------------------|-----------|------------------------------|-----------------|------------------|------------------|--------------------|----------------------|------------------------------|-----------------|------------------|------------------|--------------------|----------------------|------------------|------------------|
| | | Observations of SWE/Depth | | | Models | | | Observations of SWE/Depth | | | Models | | | | |
| | | | | | All (33) | Calibrated (18) | Uncalibrated (15) | | | | All (33) | Calibrated (18) | Uncalibrated (15) | | |
| | | Maximum | Number | Mean | Minimum | Maximum | Mean | Maximum | Minimum | Mean | Maximum | Minimum | Mean | | |
| Alptal (Switzerland) | 2002–2003 | 160 | 17 | 0.5 | 0.2 | 0.9 | 0.4 | 0.5 | 257 | 20 | 1.0 | 0.5 | 1.3 | 0.9 | 1.0 |
| | 2003–2004 | 90 | 19 | 2.4 | 0.6 | 6.9 | 2.4 | 2.5 | 295 | 27 | 1.0 | 0.2 | 1.7 | 0.9 | 1.1 |
| BERMS | 2002–2003 | 57 | 8 | 0.8 | 0.1 | 1.7 | 0.6 | 1.0 | 74 | 6 | 0.9 | 0.3 | 1.6 | 0.8 | 1.1 |
| (Canada) | 2003–2004 | 65 | 15 | 1.9 | 0.8 | 3.9 | 1.8 | 1.9 | 73 | 8 | 1.3 | 0.3 | 2.7 | 1.2 | 1.4 |
| Fraser | 2003–2004 | 122 | 6 | 0.7 | 0.1 | 2.7 | 0.5 | 0.9 | 210 | 6 | 1.0 | 0.4 | 2.0 | 0.9 | 1.1 |
| (USA) | 2004–2005 | 176 | 10 | 1.0 | 0.2 | 2.1 | 0.9 | 1.0 | 266 | 10 | 1.1 | 0.5 | 1.9 | 0.9 | 1.3 |
| Hitsujigaoka (Japan) | 1997–1998 | 73 ^b | 28 ^b | 0.9 ^b | 0.3 ^b | 1.7 ^b | na | na | 86 ^b | 115 ^b | 0.9 ^b | 0.3 ^b | 1.7 ^b | na | na |
| Hyytiälä | 2003–2004 | 94 | 9 | 0.9 | 0.1 | 3.7 | 0.5 | 1.2 | 56 ^b | 215 ^b | 1.1 ^b | 0.5 ^b | 3.0 ^b | 1.0 ^b | 1.2 ^b |
| (Finland) | 2004–2005 | 82 | 6 | 1.4 | 0.4 | 4.8 | 1.2 | 1.7 | 38 ^b | 193 ^b | 2.0 ^b | 0.3 ^b | 5.6 ^b | 1.9 ^b | 2.1 ^b |

^aNotation: na denotes data not available.

^bIndicates normalized RMSE of depths (normalized RMSE of SWE at all other sites).

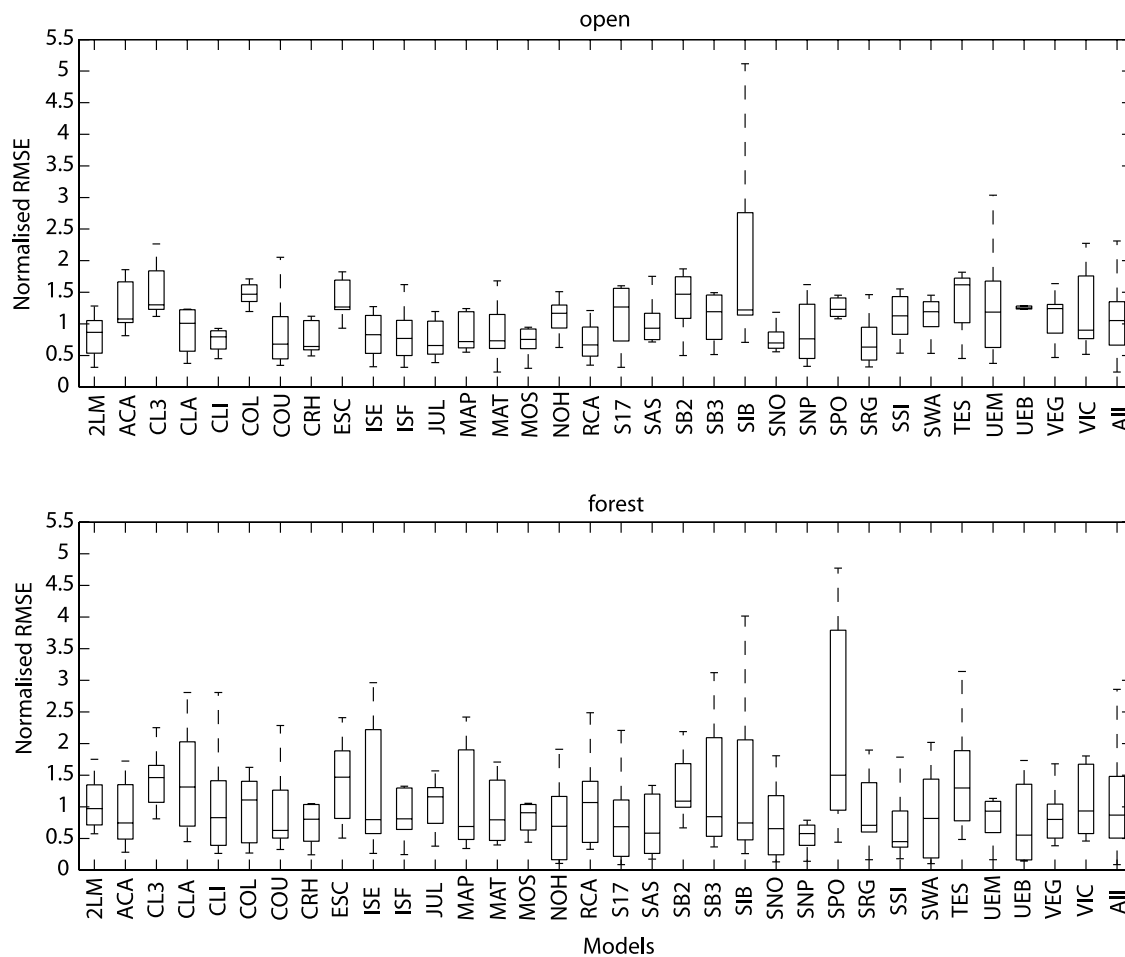


Figure 6. Box plot summaries [Tukey, 1977] describing the performance of individual models and all models, combined at all locations and years at open sites and forest sites. Each box has horizontal lines (solid) at lower quartile, median, and upper quartile values; whiskers (dashed lines) extend from the end of each box to 1.5 times the interquartile range; outliers beyond this range are omitted.

3.2. Consistency of Model Performance

[34] Collective performance of all models is illustrated by the positions of model averages relative to observed values in Figures 1–5. Owing to differences in methods of collecting snowpack data at different sites, and the potential for variations in the exact location of evaluation data relative to the site of meteorological observations, it is only valid to compare between years at the same site and not between sites or locations. Visual categorization of whether the modeled average was above, below or roughly equal to the observations throughout each winter suggested that there was a difference between years only at the BERMS forest site (i.e., model underestimation in 2002–2003 and overestimation in 2003–2004). Consequently, collective model performance could be generally considered as consistent between years.

[35] Consistency of individual model performance, shown by Figure 7 and determined by the Kendall rank correlation test (Table 8), between years at the same site and location was statistically significant at all sites other than the forest site at Alptal. Correlations were always stronger at the open site than the forest site at each location suggesting that a model that performed well for 1 year at an open site was more likely

to perform well in the subsequent year. At forest sites there was more variability in relative model performance between years. Correlations between open and forest sites in the same year and location were not statistically significant at any location other than the first year at Hitsujigaoka and Hyytiälä, which only showed weak positive correlations. Consequently, there was little consistency in the relative performance of a model between forest and open sites for the same year and location.

3.3. Influence of Calibration and Use of Precipitation Data on Model Performance

[36] Out of the 33 models, 18 chose to calibrate at forest sites (other than Hitsujigaoka where calibration was not possible) in the first year. At Hyytiälä, direct comparison between forest and open sites was not possible as SWE and depth observations were used for evaluation at forest and open sites, respectively. For all models in the first year at forest sites, the mean RMSE of both calibrated and uncalibrated models was always less than the RMSE at the corresponding open sites (Table 7). Conversely, in the second year, mean RMSE at forest sites were greater at all locations other than Fraser (where the RMSE were within 0.1 of each other). There was never a decrease in RMSE from the first to the

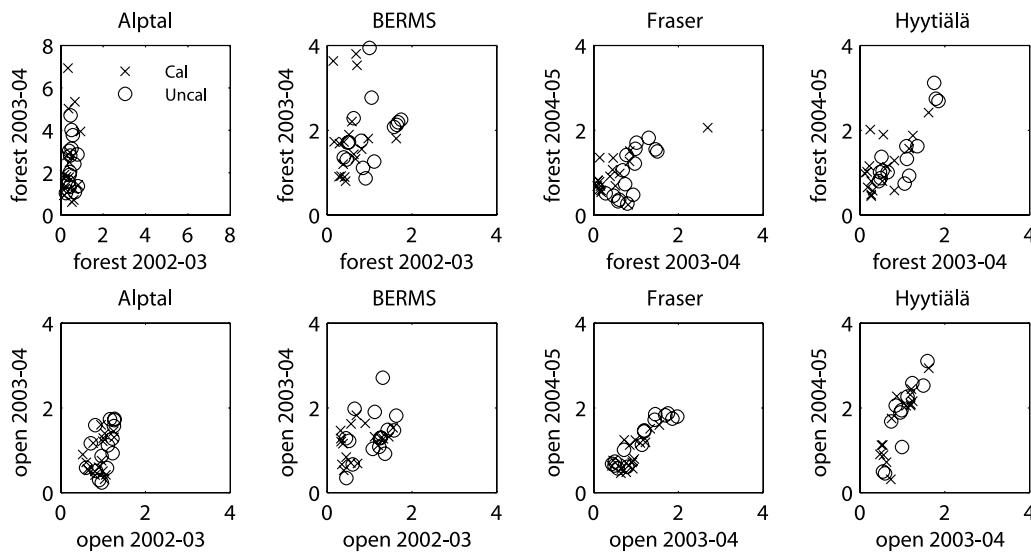


Figure 7. Performance of calibrated and uncalibrated models at the same locations, sites and years (see Table 8 for correlation coefficients). Performance is quantified by RMSE (normalized by the standard deviation of observed values) between modeled and observed SWE at all sites other than open sites at Hyytiälä where snow depths are used instead.

second year at open or forest sites and, as a proportion of the RMSE in the first year, the increases in the second year were greater in the forest than the open at each location. This suggests it was easier to model in the open than in the forest in years without calibration. However, it is uncertain whether the greater increase in RMSE between years in forest than open sites was due to the benefits of calibration or the complexity of forest snow processes.

[37] The distribution of errors in calibrated and uncalibrated model subsets, shown by scatterplots in Figure 7 and box plot summaries of each subset in Figure 8, indicated that calibrated models always performed at least as well as, or better than, uncalibrated models at forest and open sites (Table 7). At forest sites, the decrease in calibrated model performance from the first to the second year occurred at all locations and was greater (as a proportion of the RMSE in the first year) than uncalibrated models. Model performance at open sites either remained unchanged or decreased between years, although the decrease was always less than at the corresponding forest site for calibrated models. This was not the case for uncalibrated models. Of the calibrated and uncalibrated subsets at each site, year and location (as in Figure 7), there was a significant difference (Wilcoxon rank-sum test, p value < 0.05) between subsets at forest sites in the first year at BERMS, Fraser and Hyytiälä, and at the open site in the second year at Fraser. All other comparisons of

calibrated and uncalibrated subsets were not significantly different from each other.

[38] Four models (COL, CRH, NOH, SNO) had to repartition precipitation using different criteria than in Table 3 owing to inflexibility of model algorithms. However, none exhibited extreme overestimation or underestimation at any location. Consequently, the alteration of precipitation data by models in order to participate in the intercomparison did not appear to have caused systematic biases.

[39] In summary, this shows that calibration of forest models provided statistically significant lower RMSE than uncalibrated models for the calibration periods at three of the four locations. However, the benefits of calibration did not translate between years and those benefits gained by models calibrated for forest snow processes were not translated to open conditions. This confirms that consideration of canopy processes rather than calibration is required for reliable long-term operation of forest snow models, which is consistent with recent thinking in hydrological modeling [Sivapalan *et al.*, 2003].

4. Conclusions

[40] The performance of multiple snowpack models in forested conditions has essentially been unknown. This study provides the first assessment of the performance of a large

Table 8. Kendall's Correlation Coefficients of Individual Model Performance (Calibrated and Uncalibrated Models) Between Sites and Years at Each Location^a

| Location | Forest Year 1 | Forest Year 2 | Open Year 1 | Open Year 2 | Forest Year 1 | Open Year 1 | Forest Year 2 | Open Year 2 |
|----------------------|---------------|---------------|-------------|-------------|---------------|-------------|---------------|-------------|
| Alptal (Switzerland) | 0.17 | | 0.33 | | 0.21 | | −0.22 | |
| BERMS (Canada) | 0.26 | | 0.28 | | 0.09 | | 0.04 | |
| Fraser (USA) | 0.31 | | 0.65 | | 0.13 | | 0.17 | |
| Hitsujigaoka (Japan) | na | | na | | 0.29 | | na | |
| Hyytiälä (Finland) | 0.50 | | 0.73 | | 0.32 | | 0.24 | |

^aItalics indicate where the correlation is significantly different from zero (p value < 0.05); na denotes data not available.

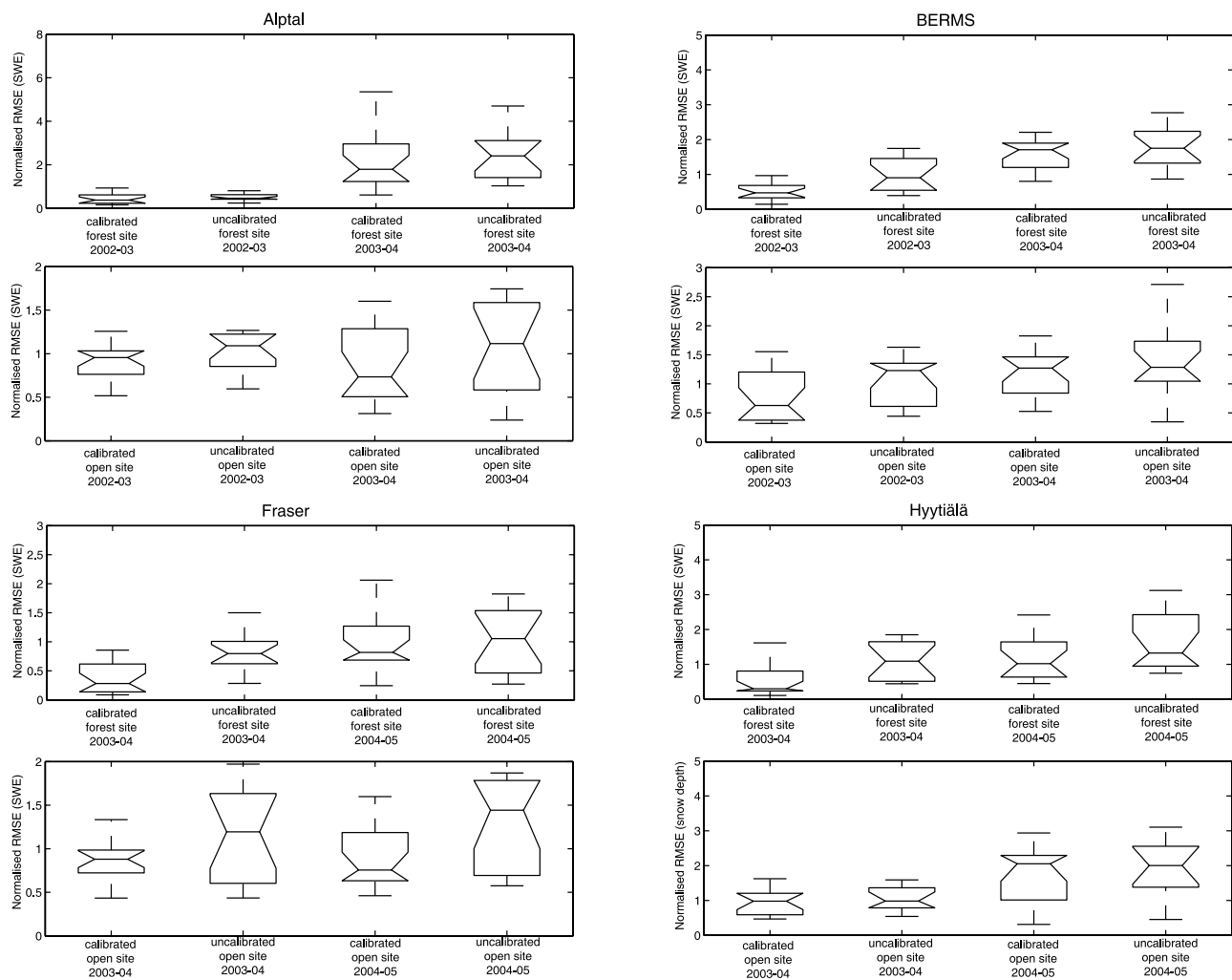


Figure 8. Box plot summaries [Tukey, 1977] of calibrated and uncalibrated model performance by location, site and year. Each box has horizontal lines (solid) at lower quartile, median, and upper quartile values; notches in vertical lines of each box represent uncertainty around the median (boxes whose notches do not overlap indicate that the medians of the two groups differ at the 5% significance level); whiskers (dashed lines) extend from the end of each box to 1.5 times the interquartile range; outliers beyond this range are omitted.

number (33) of snow models of varying complexity and purpose, across a wide range of climatological, hydrometeorological and forest canopy conditions.

[41] Divergence and convergence of modeled estimates of SWE and snow depth at forest sites resulted from cumulative effects of precipitation and air temperature events over the winter. Differences in how canopies partition snowfall events through interception and unloading was an important influence on subcanopy SWE at all sites, but the added complexity of refreezing and melt from advected energy (during warm periods) had a greater influence at the three most temperate sites. Midwinter thaws had a bigger influence than episodic increases in incoming shortwave radiation fluxes. Air temperature events that only exceeded 0°C for a few hours had little influence on divergence (primarily during accumulation) or convergence (primarily during ablation) of model results. However, events that exceeded 0°C continuously for several days were especially influential on divergence and convergence.

[42] Assessment of individual model performances indicated that there was no universal “best” model or subset of “better” models. Without calibration, it was more difficult to model SWE for forested sites than for open sites (where calibration was not possible). Correlations of model performance between years were always stronger at the open site than the forest site at each location, suggesting that model performance is most consistent at open sites. At forest sites there was more variability in relative model performance from year to year, possibly due to more complex snow processes. Correlation of individual model performances between sites in the same year and location were not statistically significant at locations other than for the first year at Hitsujigaoka and Hyytiälä, which only showed weak positive correlations. Consequently, there was little consistency between the relative performance of a model between forest and open sites in the same year and location; a good performance by a model at a forest site does not necessarily

indicate good model performance by the same model at an open site (and vice versa).

[43] Calibration of forest models provided statistically significant lower RMSE than uncalibrated models at three of the four locations when run with calibration data. However, benefits of calibration did not translate from the calibration year to other years and nor did they translate well to open conditions.

[44] This study has provided the first thorough assessment of the shortcomings of a highly representative population of forest snow models currently used for multiple research and operational purposes; it both highlights and quantifies the need for improvement. Further analysis of these results will focus on individual components of the mass and energy balance in response to see which components (if any) can be isolated and given particular consideration for future model development.

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